Cenozoic biostratigraphy, chronostratigraphy and paleoceanography in the Boso Peninsula and Bandai Volcano in the Aizu region, East Japan

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Abstract

The Boso Peninsula is a geologically active region where Cenozoic marine sediments formed in a wide variety of depositional and tectonic environments, including ocean basins, trench, trench-slope basins, forearc basins, and shelf to coastal zones. Radiolarians are key to dating most of these sedimentary rocks. In the northern part of the peninsula, Quaternary sedimentary sequences consisting mainly of siltstone and sandstone crop out along canyons of the Yoro and other rivers. There is no better place in the world than the Yoro canyon to correlate the Pleistocene geomagnetic polarity records to marine micro-biostratigraphy, oxygen isotope records, and radiometric ages from volcanic ash layers. This feature is of great benefit to establishing the boundary stratotype of the lower and middle parts of the Pleistocene Stage. In the more mountainous area to the south, visitors can trace the geological history back to middle Miocene through continuous sedimentary sequences. The earliest fossils imprinted in the rock of the peninsula are of early Cretaceous radiolarians from the Mineoka ophiolite complex. Since the Early Miocene the southern part of the peninsula was covered by seas and close to the trench where the Philippine Sea Plate subducts under the North American Plate. Continual subduction of the oceanic plate resulted in a pile of accreted Miocene sedimentary rocks in the southern part of the peninsula. Cover sediments unconformably resting on those accretionary prisms are thought to represent trench-slope basin deposits. Well-developed uplifted marine terraces in the

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southern portion of the peninsula represent the Holocene-continuing seismic activity associated with the earthquake cycle.

Mount Bandai is a cone-shaped active stratovolcano. Past eruptions and collapses of mountain body formed a dammed lake, Lake Inawashiro, the fourth largest lake in Japan, to the south and created the numerous beautiful lakes in the forest land to the north. Bandai Volcano and its surrounding area was registered as a Japanese Geopark in 2011.

Key words: fore-arc basin, trench-slope deposit, Radiolaria, microfossil, Global Boundary Stratotype Section and Point (GSSP), Tabuchi section, Bandaisan Geopark

Introduction

The Boso Peninsula in Chiba Prefecture is bordered by the Tokyo Metropolitan City in the northwest, facing Tokyo Bay to the west and the Pacific Ocean to the south and east (Fig. 1). Although its elevation (highest peak of 408 m) is quite low, vigorous erosion by river flows have formed lots of creeks displaying excellent exposures in this region, because of the rapid uplift and humid climate during the Quaternary. Such good conditions for geological observation make the Boso Peninsula one of the most well-known geological fields of the upper Cenozoic sedimentary sequence in Japan, encompassing raised fore-arc and trench-slope basin deposits and an accretionary complex of the trench–fore-arc system near the triple junction of trenches that is unique in the world. At the junction, one continental (North American Plate) and two oceanic (Philippine Sea Plate and Pacific Plate) plates meet, with the latter subducting under the former plate. The fore-arc deposits represent the Middle Miocene to Pleistocene sedimentologic, micropaleontologic, and magnetostratigraphic records, including the lower and middle parts of the Pleistocene Stage with the transition between the Matuyama and Brunhes polarity chrons – a hopeful candidate of the Global Boundary Stratotype Section and Point (GSSP). Microfossils are common to abundant in these upper Cenozoic strata. Both the siliceous and calcareous microfossils have been documented from them to determine depositional ages. These microfossils contain both low-latitude and boreal faunal and floral elements, because of the close proximity to the confluence zone of the warm Kuroshio Current and the cold Oyashio Current through time, so they provide an effective clue to reconstructing the paleoceanographic evolution of the mid-latitude western Pacific Ocean since the Middle Miocene. However, little effort has been made on this issue in the field. The accretionary prism and the trench-slope basin-fill deposits also yield well-preserved siliceous microfossils that have been studied for the reconstruction of the structural development of the trench-slope system.

Bandai Volcano is an active stratovolcano located in the Aizu area, Northeast Japan (Figs. 1, 2). Because of its beautiful conical shape it is sometimes called 'Aizu Fuji'. The mountain

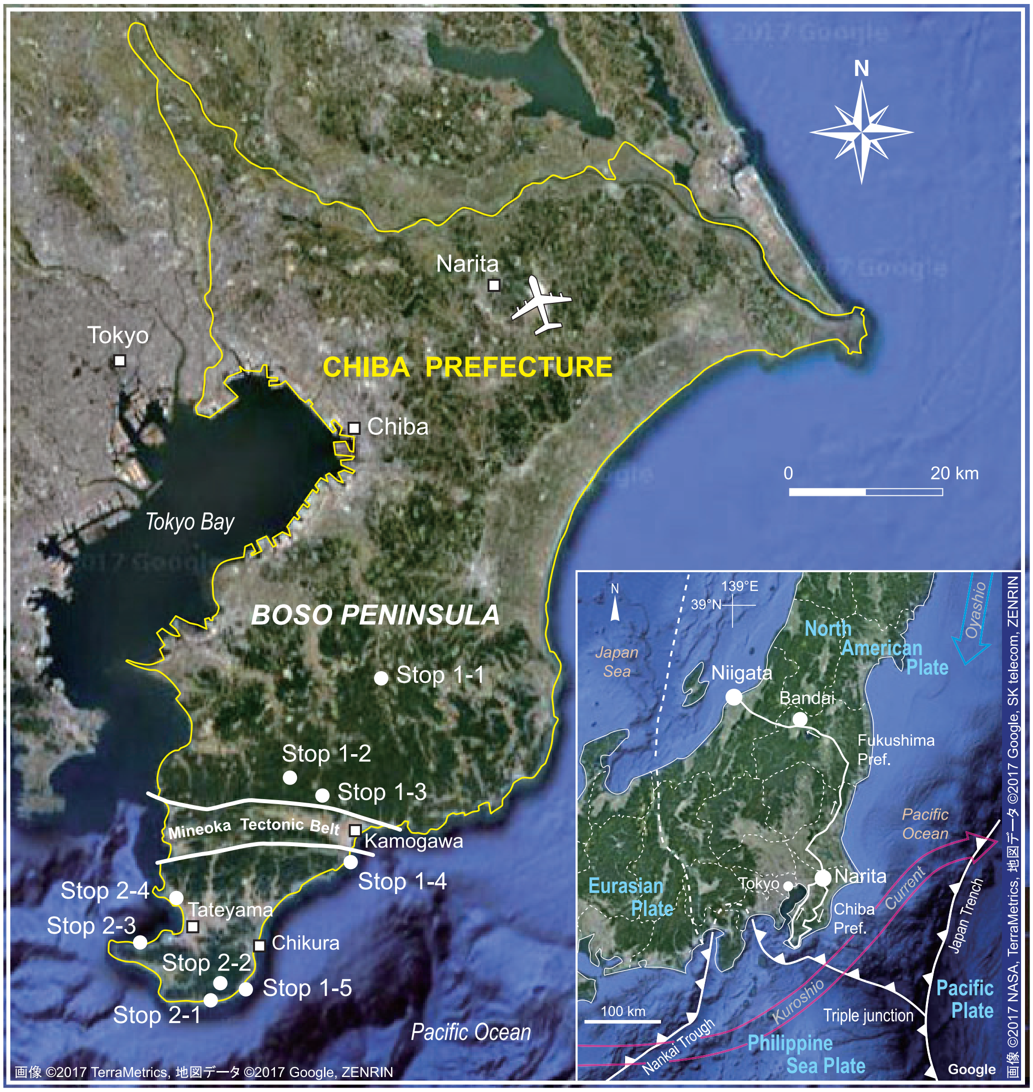

Fig. 1. Index map.

body collapsed many times during past eruptions, especially the eruption in 1888, which was the most terrible volcanic disaster within the last 150 years (i.e., since the beginning of the Meiji Era) in Japan. However, it resulted in a beautiful and magnificent landscape, and so the Bandai Volcano area was admitted to the Japan Geopark Network in 2011.

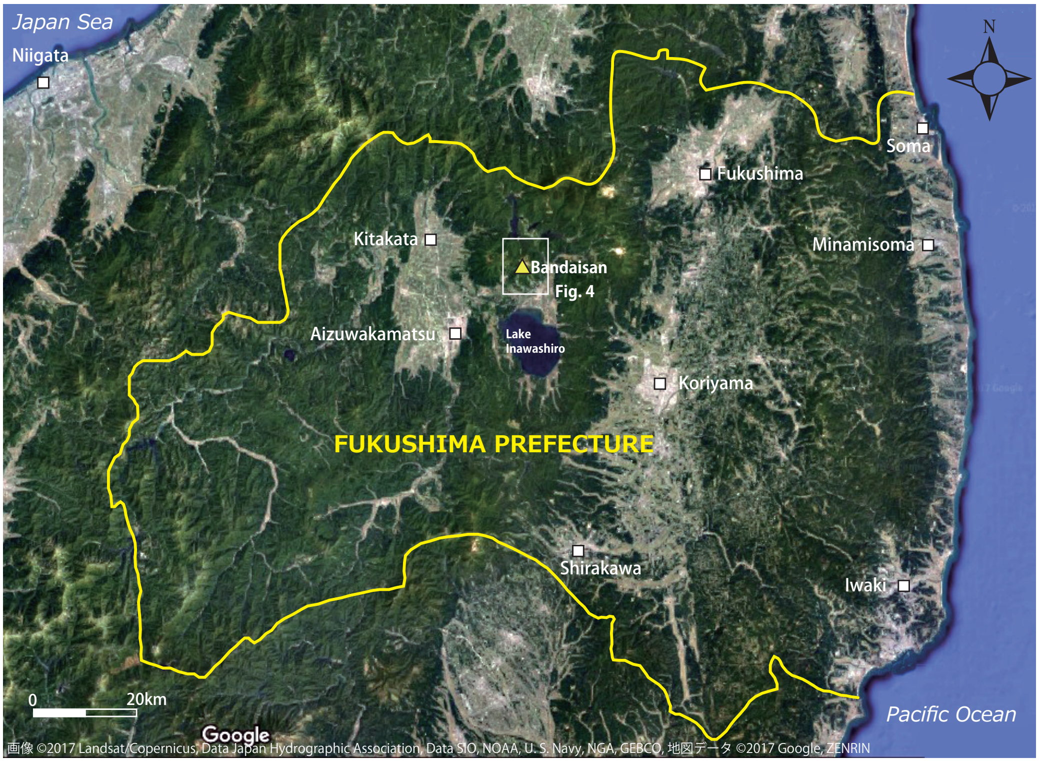

Fig. 2. Locality of Bandaisan (Bandai Volcano).

Geology and Micropaleontology

1. Boso Peninsula

The Boso Peninsula can be divided into three geological zones: the northern area where the Middle Miocene to Pleistocene normal sediments distribute, the Mineoka tectonic belt characterized by an ophiolitic complex and Lower Miocene accretionary prism, and the southern area associated with a Miocene to Pliocene accretionary prism that are unconformably overlain by Middle Miocene to Pleistocene cover sediments (Figs. 1, 3). These zones are bordered by major faults extending in an E-W direction. Across the Mineoka belt the sedimentary facies, deformation of strata, and geologic history change abruptly. The northern area is of interest for biostratigraphy and chronostratigraphy. The Mineoka belt and the southern portion compose a unique field where we can see the young trench-slope tectonic system in onshore sections. Much attention has recently been focused on the origin and evolution of the system through studies of sedimentology and structural geology. Microfossils have contributed in dating these sediments and reconstructing a detailed tectonic and sedimentological history.

Northern area: A thick marine sedimentary sequence of the Awa, Kazusa, and Shimosa Groups in ascending order distribute in this area. These groups represent the history of fore-arc basins and display evidence of a progressive shoaling of marine environments from slope to shelf environments through the Middle Miocene to Quaternary (Kitazato, 1997; Ito et al., 2016). These strata become progressively younger to the north, but are gently folded with E–W axes near the Mineoka tectonic belt.

The Awa Group with a thickness of 3,000 m, ranging in age from 16 to 3 Ma, is subdivided into the Kanigawa, Kinone, Amatsu, Kiyosumi, and Anno Formations. The Miura Group, whose stratotype is placed in the Miura Peninsula, is an equivalent unit to the Awa Group. The facies of the Kanigawa to Kinone Formations indicates an upward deepening trend and the Amatsu Formation consists mainly of hemipelagic mudstone. The Kiyosumi and Anno Formations consist of alternations of sandstone and mudstone representing flysh facies deposited in submarine fan environments (Tokuhashi, 1979; Nakajima et al., 1981). Micropaleontological evidence suggests deposition of the Awa Group in the fore-arc basin began in the mid Miocene (16–15 Ma). The Amatsu Formation is a thick (1,000 m) hemipelagic sequence that deposited during 12 to 5.5 Ma and intercalates numerous ash layers of which characteristic ones are numbered from AM1 to AM98. This formation yields calcareous and siliceous microfossils and has been dated by a lot of biostratigraphic works (planktonic foraminifera, Oda, 1977; calcareous nannofossils, Kanie et al., 1991; Mita and Takahashi, 1998; Kameo et al., 2002, 2010; Kameo and Sekine, 2013; Radiolaria, Motoyama and Takahashi, 1997; Sawada et al., 2009; diatoms, Haga and Kotake, 1996; Watanabe and Takahashi, 1997, 2000; Takahashi et al., 1999). Kitazato (1997) estimated paleodepths of 1,000 to 2,000 m for the Amatsu to Anno Formations.

The Awa Group is separated from the overlying Kazusa Group by a gently angular unconformity called the Kurotaki Unconformity. The Kazusa Group was formed by sediment accumulation in a fore-arc basin during 2.4 to 0.45 Ma (Ito et al., 2016). The best exposures of this group are found along the Yoro River where 3,000 m of north-dipping mudstones, sandstones, and tuff beds are displayed. The basal conglomerate of the Kurotaki Formation unconformably overlays the Awa Group. Erosion of the underlying sediments by this unconformity becomes greater to the east. Calcareous microfossils are abundant in the Kazusa Group and have been well investigated in biostratigraphic and paleoceanographic works (e.g., Aoki, 1963, 1968; Kitazato, 1977; Nishida, 1977; Oda, 1977; Takayama and Ikeno, 1977; Sato et al., 1988, 1999; Igarashi, 1994), while diatom biostratigraphic study is restricted to Cherepanova et al. (2002) and no radiolarian works have been published, so that much more work is needed to clarify the nature of siliceous fauna and flora. Studies on the oxygen isotope stratigraphy has been done by Okada and Niitsuma (1989), Pickering et al. (1999) and Tsuji et al. (2005). The lower part of the Kazusa Group was deposited in bathyal environments with a maximum paleodepth of ~1,500 m (Kitazato, 1997) and the middle part of this group of late Pleistocene age represents the final phase of deep-sea deposition in the Boso area (Ito and Katsura, 1992). The overlying Shimosa Group of late Pleistocene age is composed mainly of sandstone deposited in shelf to coastal environments. This group has yielded abundant fossil marine molluscan shells. A few fossil mammals have been discovered from this group.

We have preliminarily investigated radiolarian assemblages from the middle to upper Miocene Amatsu Formation using samples collected by Sawada et al. (2009) to discuss paleoceanography. The radiolarian assemblages comprising 95 taxa include 17 warm-water (low latitude) taxa (*Anthocyrtidium* spp., *Calocycletta caepa*, *Carpocanium* spp., *Collosphaera* spp., *Dictyocoryne* spp., *Diartus hughesi*, *D. petterssoni*, *Didymocyrtis laticonus*, *D. penultima*, *Heliodiscus* spp., *Lithopera renzae*, *L. thornburgi*, *Lophocyrtis pentagona*, *Phormostichoartus corbula*, *P. doliolum*, *Phorticium pylonium* group, *Stylodictya multispina* group), and 12 cool-water (high latitude/cosmopolitan) taxa (*Amphistylus angelinus*, *Axoprunim bispiculum*, *Cyrtocapsella japonica*, *C. tetrapera, Larcopyle polyacantha* group, *Lithelius minor* group, *Lophocyrtis aspera*, *Spongodiscus gigas*, *S. sol, Stylosphaera timmsi*, *Thecosphaera dedoensis*, *T. pseudojaponica*). The faunal composition suggests the studied region was in the temperate climatic zone influenced by both warm and cool water currents. The fluctuation patterns in the relative abundance of warm-water taxa indicate that the Kuroshio Current was strengthened during three intervals (12.5 Ma, 11.5 to 10.5 Ma, and 9.5 to 8.5 Ma).

Mineoka tectonic belt: This zone represents 'basement rocks' of the Boso Peninsula. It involves the Mineoka ophiolitic complex comprising various sized exotic blocks of ultramafic rocks (peridotite, serpentinite), basalt, dolerite, diorite, sandstone, shale, chert, and limestone (Takahashi et al., 2012, 2016). Middle Eocene radiolarians occurred from a siliceous mudstone nodule (Kawakami, 2004); Paleocene to Oligocene planktonic foraminifers were found from limestone blocks (Mohiuddin and Ogawa, 1996, 1998a, b); and bedded chert yielded early Cretaceous radiolarians (Ogawa and Sashida, 2005). These suggest that the Mineoka ophiolitic complex includes the oldest rocks in the Boso Peninsula. A great deal of attention has been focused on the origin and evolution of this ophiolitic complex through petrological and geochronological studies (e.g., Ogawa and Naka, 1984; Arai, 1991; Fujioka et al., 1995; Hirano et al., 2003; Takahashi et al., 2012). Some of these investigations link the origin of the complex to the Philippine Sea Plate, while some implicate the lost Mineoka Plate, which is thought to have existed in the western Pacific during the Paleogene, but has now disappeared because of subduction of the plate into the mantle (Hirano et al., 2003). The ophiolitic complex might have been squeezed out to the surface from great depths along a major thrust fault system.

The Mineoka ophiolite complex is surrounded by the Hota Group, which consists of mudstone, sandstone and tuffs associated with deformational structures such as thrusts, folds, repetitions, and shared structures indicative of an accretionary prism (Takahashi et al.,

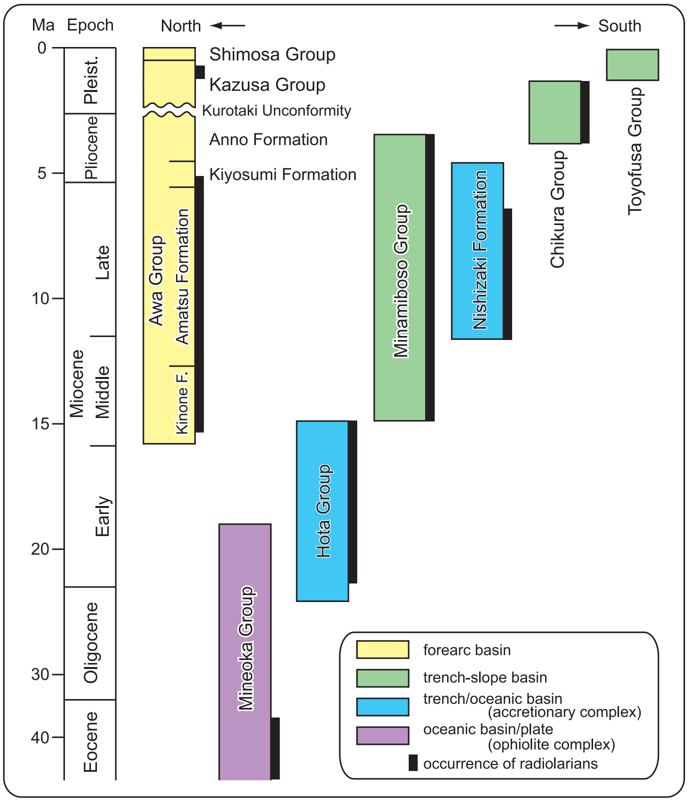

Fig. 3. Subdivision and correlation of Cenozoic rocks in Boso Peninsula.

2016). Radiolarians from the Hota Group indicate an early Miocene age (Saito, 1992).

Southern area: The oldest rocks in this area are represented by the accretionary complex Hota Group. Mudstones of this group yield latest Oligocene diatoms (Suzuki et al., 1996) and Early Miocene radiolarians (Saito, 1992) while Paleogene radiolarians were reported from gravels of tuff and mudstone included in the group (Kawakami, 2004). There is a younger accretionary prism called the Nishizaki Formation. Radiolarians indicate a Late Miocene age for this formation (Kawakami, 2001; Yamamoto and Kawakami, 2005). These accretionary complexes are unconformably overlain by cover sediments that are assigned to the Minamiboso, Chikura and Toyofusa Groups. The Minamiboso Group consists of eight formations that represent separated small trench-slope basins varying in age from the Middle Miocene to Pliocene (Kawakami and Shishikura, 2006). The Chikura Group in this area consists of Upper Pliocene to Lower Pleistocene marine deposits (siltstone, sandstone, and conglomerate) and is divided into the Shirahama, Shiramazu, Mera, and Hata Formations, in ascending order (Kawakami and Shishikura, 2006). These strata are gently folded with E–W axes becoming progressively younger to the north. Molluscan fossils including *Calyptogena*, which represents cold seep communities in deeps-sea environments,

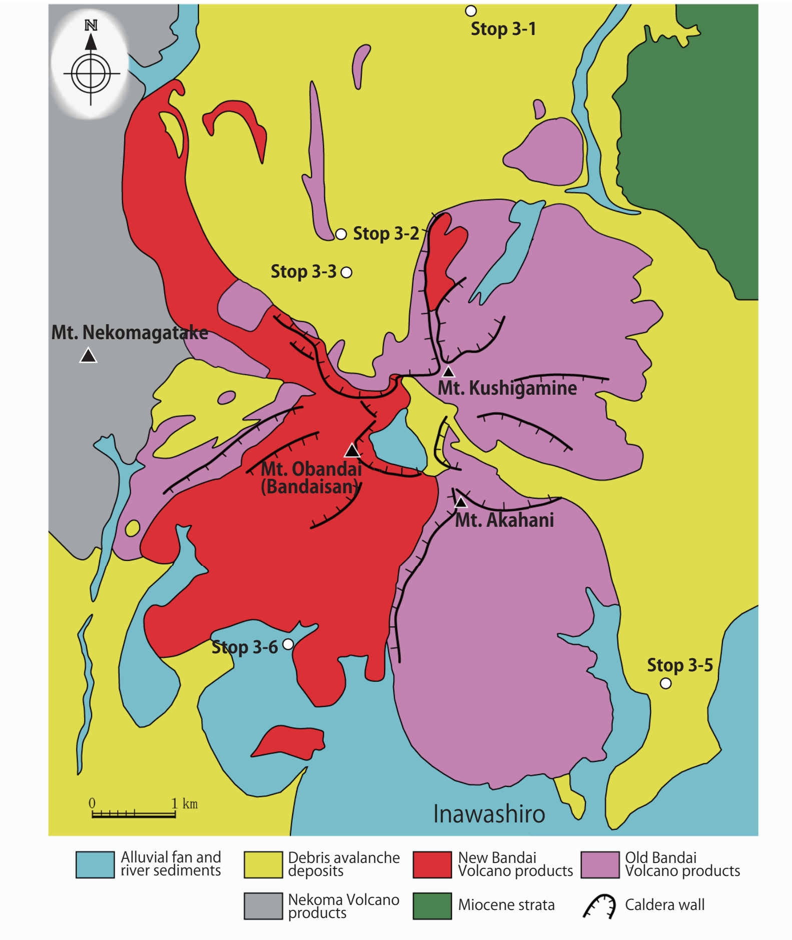

Fig. 4. Geological map of Bandai Volcano. After Taketani et al. (2015), simplified from Chiba and Kimura (2001).

and various microfossils including foraminifera, calcareous nannofossils, radiolarians, and diatoms occur in these formations. The Toyofusa Group is a Pleistocene representative of the cover sediments in the trench-slope system.

2. Bandai Volcano and Bandaisan Geopark

Bandai Volcano, an active volcano on the east Japan volcanic front, is located in the Aizu area of Fukushima Prefecture, Northeast Japan (Fig. 2). The volcano has three peaks: Mt. Obandai (Bandaisan) (1,816 m), the highest peak of the volcano, Mt. Kushigamine (1,636 m), and Mt. Akahani (1,427 m) (Fig. 4).

Bandai Volcano is covered with thick layers of pyroclastic flow sediments in addition to andesitic lavas. The eruptive history of Bandai Volcano has been researched mainly by tephrochronology (Yamamoto and Suto, 1996; Chiba and Kimura, 2001). The volcano became active about 700,000 years ago (Mimura, 1994). First, a large mountain body (Old Bandai Volcano), which includes Mt. Kushigamine and Mt. Akahani, was formed (Fig. 4). About 50,000 years ago a large part of the southwestern slope of Old Bandai volcano collapsed during a Plinian eruption (Yamamoto and Suto, 1996). The debris avalanche spread across a large area and Lake Inawashiro was born by natural damming of a river (Nagahashi et al., 2016). In the collapsed area, volcanic activity became high, which led to the formation of Mt. Obandai and its northern neighbor Mt. Kobandai (New Bandai Volcano) (Chiba and Kimura, 2001) (Fig. 4).

Most of Mt. Kobandai collapsed during a phreatic explosion in 1888 and a large horseshoe-shaped caldera was formed (Sekiya and Kikuchi, 1889). The collapse brought rapid debris avalanches to the north this time, burying many villages and killing 477 people (Nakamura, 1978). On the other hand it formed about 300 beautiful dammed lakes, magnificent landscapes and a characteristic natural environment. The area around Bandai Volcano was designated as Bandai Asahi National Park in 1950.

In 2010 the Bandaisan Geopark Council was established for conservation and utilization of natural and cultural resources related to Bandai Volcano. The Bandai Volcano area was admitted to the Japan Geopark Network in 2011 by the Japan Geopark Committee. The main theme of the Bandaisan Geopark is to clarify the birth and transition of Bandai Volcano, especially large scale change of topography and natural environment caused by mountain collapse and the following debris avalanche, and furthermore to study the volcano's influence on regional history and culture. The Bandaisan Geopark Council is now making an effort to join the UNESCO Global Geopark Network.

Description of field stops

STOP 1

Stop 1-1: Tabuchi section—Boundary section of the Lower/Middle Pleistocene, Plio-Pleistocene fore-arc basin deposits (Kokumoto Formation, Kazusa Group)

The Tabuchi section is located about 40 km south of Narita Airport (Fig. 1). Here a sequence of Pleistocene marine sedimentary strata is exposed in its most complete succession. The sedimentary sequence at the Tabuchi section is a hopeful candidate of the GSSP for the Lower/Middle Pleistocene (Aida, 1997), which is in competition with the other candidates from Italy toward the formal certification of the GSSP and the 'Chibanian Stage' by the IUGS. The boundary of the Lower/Middle Pleistocene is defined by the youngest geomagnetic polarity reversal, the Matuyama–Brunhes reversal event, dated at 0.78 Ma when the Earth's magnetic field switched from the reversed to the normal mode. The Tabuchi section is superior to the others in having a detailed magnetic polarity record around the transition from Matuyama to Brunhes in a high-sedimentation-rate (200 cm /

Fig. 5. Massive siltstone of the Kokumoto Formation, Kazusa Group, recording the youngest geomagnetic polarity reversal, the Matuyama-Brunhes boundary, on a cliff of the Tabuchi section along the Yoro River. Byakubi-E tephra gently dipping to the left (north) just above the third red mark from the bottom has been dated to 772.7 ±7.2 kiloyears ago using U–Pb zircon dating (Suganuma et al., 2015).

kiloyear) sedimentary sequence (Okada and Niitsuma, 1989; Kazaoka et al., 2015; Nishida et al., 2016; Okada et al., 2017). Most recently this magnetostratigraphic record has been correlated with an oxygen isotope chronology using foraminiferal tests from the same section (Suganuma et al., 2015), suggesting that the polarity transition falls within the marine isotope stage (MIS) 19. The polarity boundary has been calibrated at 770.2 ±7.3 ka based on radiometric (U–Pb) dating for a tephra (Byakubi-E) just below the polarity boundary. The Tabuchi section is placed in a gorge along the Yoro River where fine-grained deep-sea sediments of the Kokumoto Formation, Kazusa Group, is well exposed. These sediments yield marine calcareous and siliceous microfossils as well as pollen derived from terrestrial environments. Although some low-resolution biostratigraphic study has been published for the Kazusa Group along the Yoro River (e.g., Aoki, 1963, 1968; Oda, 1977; Takayama and Ikeno, 1977; Nishida, 1977; Igarashi, 1994), it is expected that new microfossil-based studies will provide high-resolution paleoclimatic and paleoceanographic reconstructions for mid-Pleistocene central Japan.

When we stand on the dry river floor the escarpment on our left marks the position of the polarity boundary (Fig. 5). We can see colored pins that mark stratigraphic horizons of samples for magnetostratigraphy, of which red and green ones are of reversed and normal polarity, respectively, and yellow ones are of transitional nature. Byakubi-E tephra, gently

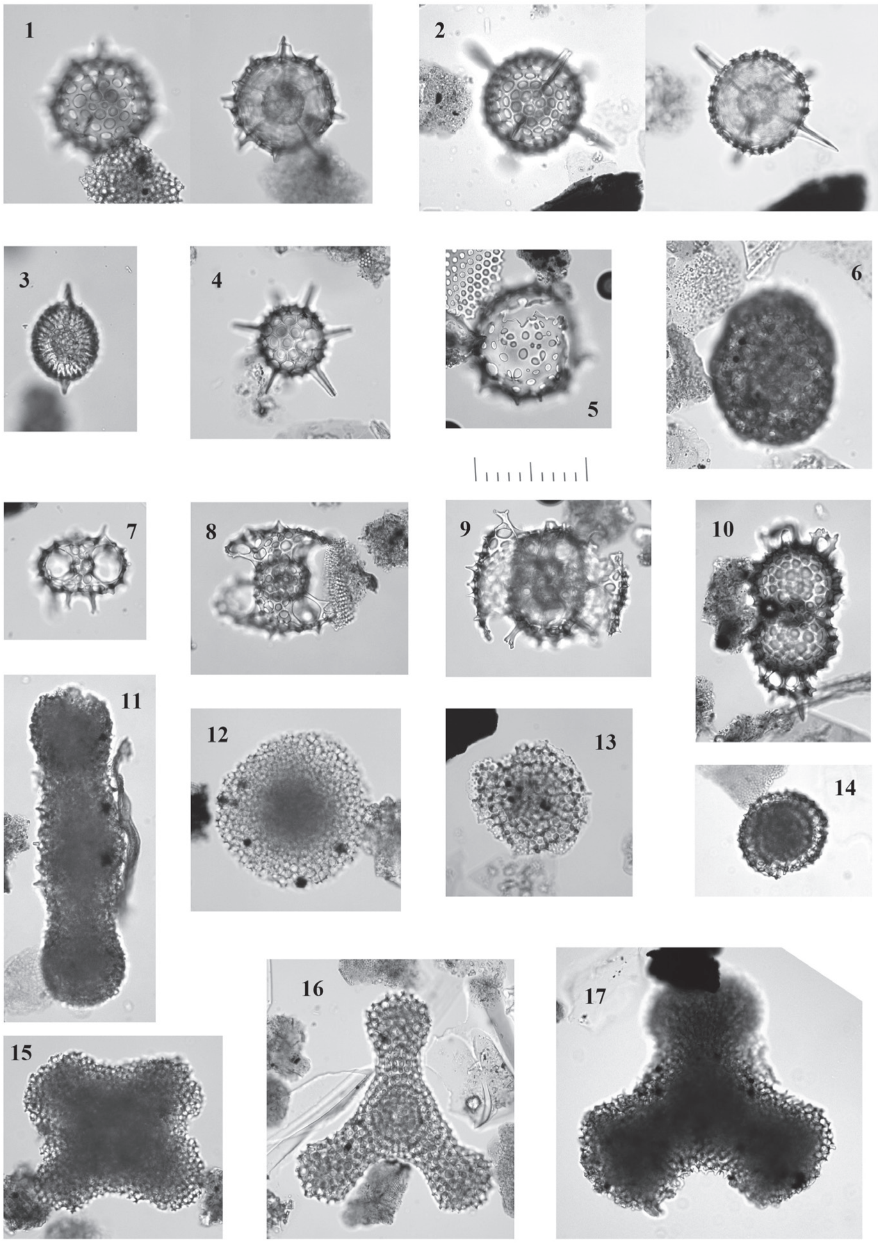

Fig. 6. Radiolarians from the Kokumoto Formation (Early-Middle Pleistocene): **1.** *Actinomma leptodermum* (Jørgensen) (sample KG7), **2.** *Hexacontium pachydermum* Jørgensen (sample KG13), **3.** *Druppatractus irregularis* Popofsky (sample YW11), **4.** *Acanthosphaera circopora* Popofsky (sample YN7), **5.** *Acrosphaera spinosa* (Haeckel) (sample YW11), **6.** *Larcopyle buetschlii* Dreyer (sample KG11), **7.** *Tetrapyle* sp. (sample KG13), **8.** *Tetrapyle circularis* Haeckel (sample YW5), **9.** *Phorticium pylonium* Haeckel (sample YW1), **10.** *Didymocyrtis* sp. (sample YW3), **11.** *Spongocore cylindrica* (Haeckel) (sample KG29), **12.** *Spongodiscus resurgens* Ehrenberg (sample KG7), **13.** *Stylochlamydium venustum* (Bailey) (sample KG17), **14.** *Larcospira minor* (Jørgensen) (sample YN9), **15.** *Spongaster tetras tetras* Ehrenberg (sample YW5), **16.** *Dictyocoryne profunda* Ehrenberg (sample YN9), **17.** *Dictyocoryne truncatum* (Ehrenberg) (sample YN8). Scale equals 100 μm. All specimens were collected from around Stop 1-1. See Okada et al. (2017) for sample horizons.

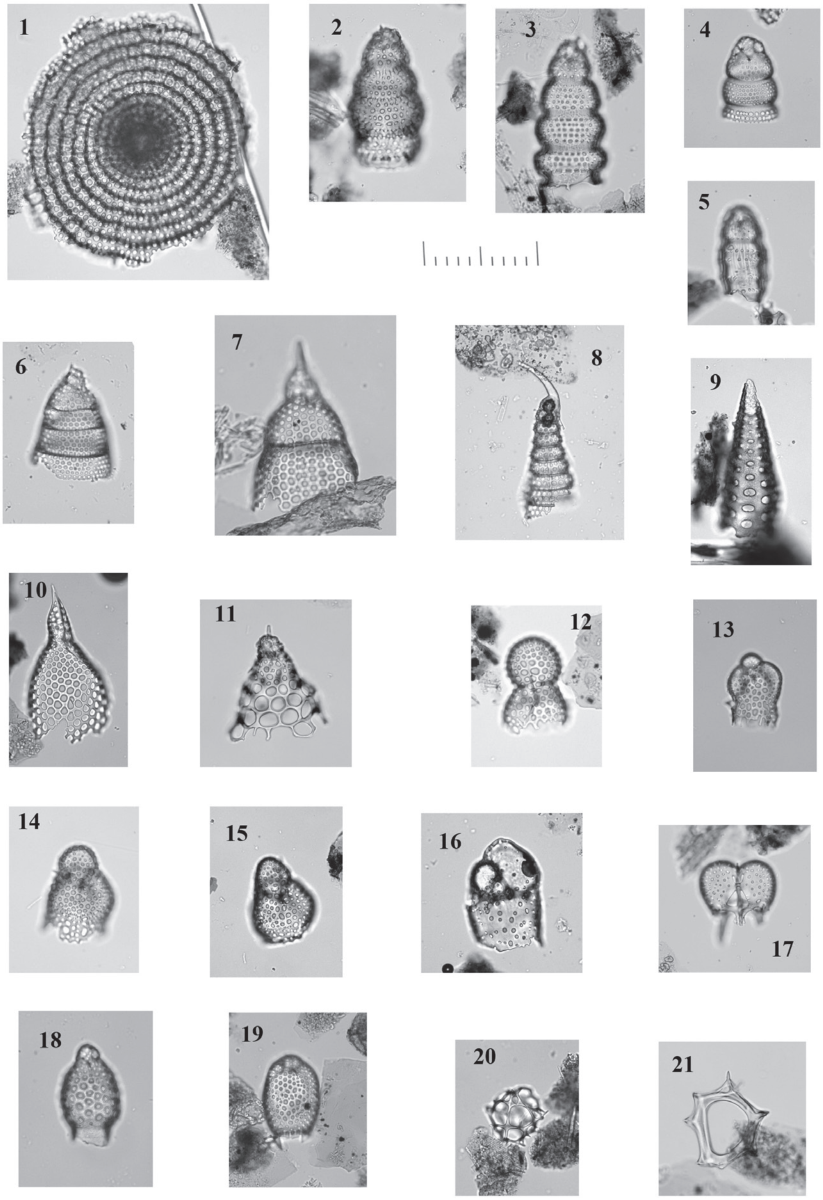

Fig. 7. Radiolarians from the Kokumoto Formation (Early-Middle Pleistocene): **1.** *Flustrella* sp. (sample YW3), **2.** *Botryostrobus aquilonaris* (Bailey) (sample YN7), **3.** *Botryostrobus auritus/australis* (Ehrenberg) group (sample YN7), **4.** *Lithamphora furcaspiculata* Popofsky (sample KG13), **5.** *Siphocampe arachnea* (Ehrenberg) (sample KG5), **6.** *Eucyrtidium hexastichum* (Haeckel) (sample KG11), **7.** *Pterocorys clausus* (Popofsky) (sample KG17), **8.** *Cyrtolagena cuspidata* (Bailey) (sample YN7), **9.** *Cornutella profunda* Ehrenberg (sample YN8), **10.** *Anthocyrtidium zanguebaricum* (Ehrenberg) (sample YN4), **11.** *Cycladophora davisiana* Ehrenberg (sample YN11), **12.** *Dimelissa thoracites* (Haeckel) (sample KG5), **13.** *Trisulcus* sp. (sample YN9), **14.** *Lithomelissa setosa* Jørgensen (sample YN9), **15.** *Lithomelissa setosa* Jørgensen (sample YN11), **16.** *Botryopyle cribosa* (Popofsky) group (sample YW7), **17.** *Phormospyris stabilis* (Goll) *scaphipes* (Haeckel) (sample YN9). **18.** *Carpocanarium papillosum* (Ehrenberg) (sample KG7), **19.** *Carpocanistrum* sp. (sample KG17), **20.** *Plectacantha oikiskos* Jørgensen (sample YW7), **21.** *Zygocircus productus* (Hertwig) group (sample YN9). All specimens were collected from around Stop 1-1. See Okada et al. (2017) for sample horizons.

Fig. 8. Upper part of the Amatsu Formation including a wide-spread tephra, Am78, so called 'OK Tuff', Koitogawa River.

dipping to the north, is placed just below the transitional horizon.

Takuya Itaki and his coworkers have started paleoceanographic work based on radiolarian assemblages from the Tabuchi section. Radiolarian fossils collected from this section are shown in Figs. 6 and 7. Their assemblages are mainly composed of warm water taxa (e.g., *Dictyocoryne* spp., *Didymocyrtis* spp., and *Tetrapyle* spp.) related to the subtropical Kuroshio Current. Cold water species such as *Lithomelissa setosa* and *Stylochlamydium venustum* are also recognized during the glacial intervals suggesting influence of the cold Oyashio Current.

Stop 1-2: Koito River—Upper Miocene fore-arc basin deposits (Awa Group)

The upper course of the Koito River is characterized by extensive exposures of Neogene marine deposits named as the Amatsu, Kiyosumi, and Anno Formations. The portion at Stop 1-2 (key ash layers AM66 to AM78) represents the coarse grained facies of the upper part of the Amatsu Formation (Fig. 8) and displays evidence of a decrease in sedimentation rate around 8 to 6 Ma. Radiolarian assemblages from this facies indicate zones RN7 (*Didymocyrtis antepenultima* Zone) to RN9 (*Stichocorys peregrina* Zone) (Sawada et al., 2009). The upper course of the Koito River is generally inaccessible except by trail because of a deep valley with vertical cliffs. At this stop there are excellent exposures of sandstone and sandy mudstone beds with many ash layers along the trail. On the cliff there are number plates pinned to the key ash layers.

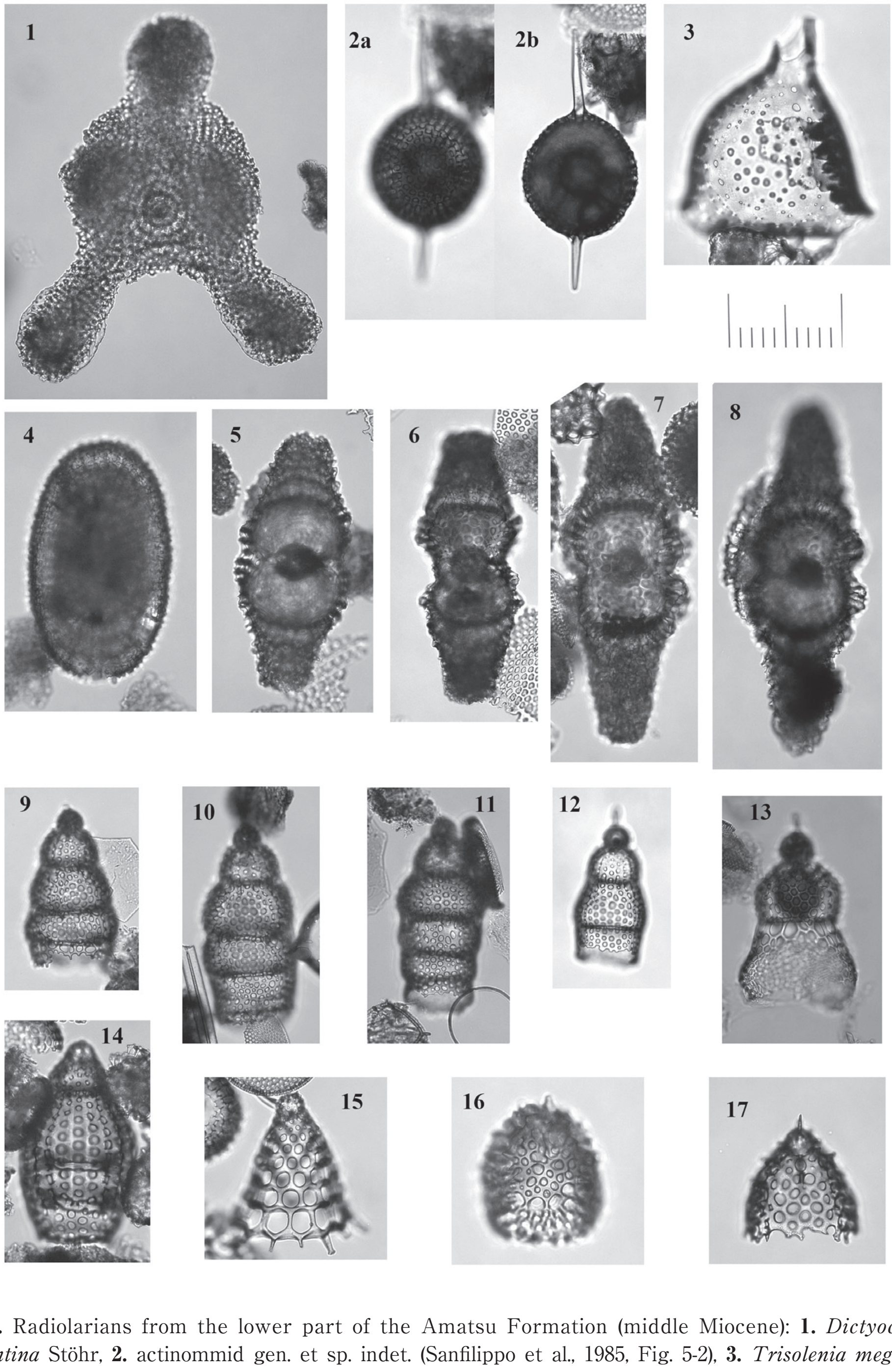

Fig. 9. Radiolarians from the lower part of the Amatsu Formation (middle Miocene): **1.** *Dictyocoryne agrigentina* Stöhr, **2.** actinommid gen. et sp. indet. (Sanfilippo et al., 1985, Fig. 5-2), **3.** *Trisolenia megalactis megalactis* Ehrenberg, **4.** *Larcopyle polyacantha polyacantha* (Campbell and Clark), **5–8.** *Didymocyrtis laticonus* (Riedel), **9–10.** *Stichocorys peregrina* (Riedel), **11–12.** *Stichocorys delmontensis* (Campbell and Clark), **13.** *Stichocorys* aff. *johnsoni* Caulet, **14.** *Eucyrtidium inflatum* Kling, **15.** *Cycladophora cosma cosma* Lombari and Lazarus, **16.** *Ceratocyrtis stoermeri* Goll and Bjørklund, **17.** *Ceratocyrtis* sp. Scale equals 100 μm. All specimens were collected from sample Boso-8 (calcareous concretion between ash layers Am1 and Am2, Meigawa River).

Stop 1-3: Meigawa River—Middle Miocene fore-arc basin deposits (Awa Group)

The Meigawa River (called as 'Kanigawa section' in some literatures), a tributary of the Kamogawa River, is located 4.5 km southeast from Stop 1-2. Along the river the Middle Miocene part of the Awa Group (Kanigawa, Kinone, and lower Amatsu Formations) is well exposed and the integrated biostratigraphy of multiple microfossil groups has been established by Takahashi et al. (1999). This stop is at the bottom of the Amatsu Formation which is defined by the first occurrence of scoria ash layers, Am1. This stratigraphic horizon is correlated to the radiolarian *Eucyrtidium inflatum* Zone and *Dorcadospyris alata* Zone (Motoyama and Takahashi, 1997). We collected a sample of a calcareous concretion between ash layers Am1 and Am2 and herein illustrate the characteristic species found in it (Figs. 9 and 10).

Stop 1-4: Futomi-hama—Lower Miocene accretionary prism (Hota Group)

This is where we can take rock samples containing radiolarians of zones RN2 (*Stichocorys delmontensis* Zone) or RN3 (*Stichocorys wolffii* Zone). The Hota Group is composed of fairly deformed mudstone and sandstone intercalating ash layers. The absence of calcareous microfossils suggests that it deposited in deep-sea environments below the calcium carbonate compensation depth (CCD) (Yamamoto et al., 2017). This group ranges from the Early Miocene to the earliest Middle Miocene in age (RN1 to RN5), indicating progressively younger sediments toward the north (Saito, 1992) and is thought to have been accreted to the island arc during 17 to 15 Ma (Yamamoto et al., 2017). The rocks here are folded mudstone and thin tuff beds cut by numerous small faults and repetitions of units can be observed (Fig. 11).

Stop 1-5: Shiramazu—Plio-Pleistocene trench-slope basin deposit (Chikura Group)

On the coast from Chikura to Shirahama, there are good exposures of the Chikura Group. These outcrops are designated as the stratotypes of the Shirahama and Shiramazu Formations. The Shirahama Formation is 100 m in thickness and consists of an alternation of sandstone and mudstone with minor conglomerate. This formation is characterized by reddish brown colored sandstone comprising volcaniclastic coarse grains and poorly preserved microfossils, presumably of Pliocene age, although no biostratigraphic works have been done yet. The Shiramazu Formation (200 m thickness) is composed of an alternation of sandstone and tuffaceous siltstone. Scoria sandstone beds are intercalated in these sediments. These sandstones often show slump structures and Bouma sequences suggesting that they are products of debris flows and turbidity currents. On the basis of calcareous nannofossil biostratigraphy and magnetostratigraphy, the Shiramazu Formation is late Pliocene in age (3.68–3.31 Ma) (Kotake et al., 1995; Kanie et al., 1997; Kameo et al., 2003). Kotake (1988) and Kotake et al. (1995) reported the occurrence of a radiolarian species

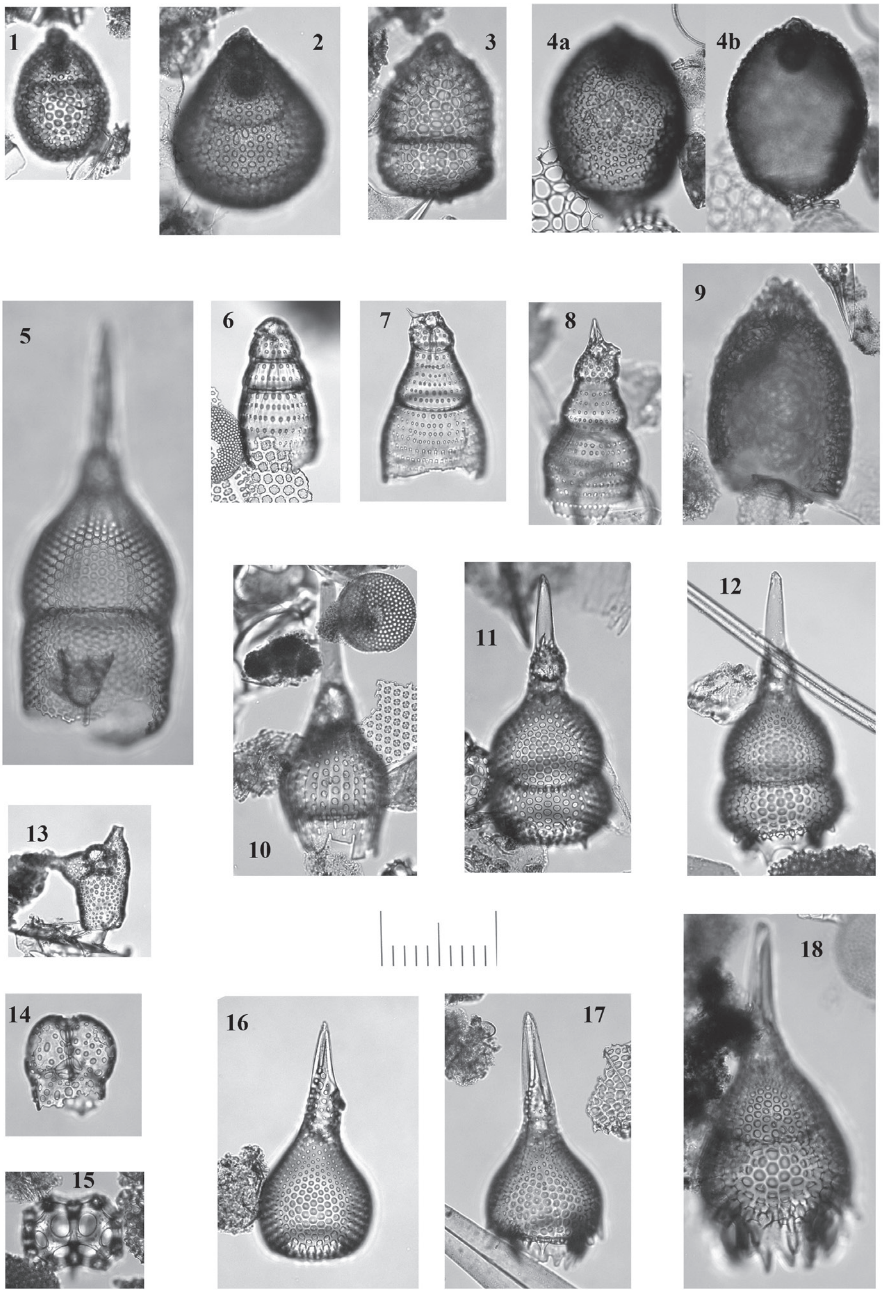

Fig. 10. Radiolarians from the lower part of the Amatsu Formation (middle Miocene): **1.** *Cyrtocapsella japonica* (Nakaseko), **2.** *Cyrtocapsella cornuta* Haeckel, **3.** *Lithopera renaze* Sanfilippo and Riedel, **4.** *Lithopera baueri* Sanfilippo and Riedel, **5.** *Calocycletta caepa* Moore, **6.** *Phormostichoartus marylandicus* (Martin), **7–8.** *Siphostichartus corona* (Haeckel), **9.** *Lithopera thornburgi* Sanfilippo and Riedel, **10.** *Calocycletta costata* (Riedel), **11–12.** *Lamprocyclas* sp., **13.** *Acrobotrys disolenia* Haeckel, **14.** *Phormospyris stabilis stabilis* (Goll), **15.** *Tholospyris anthophora* (Haeckel), **16–17.** *Anthocyrtidium ehrenbergi* (Stöhr), **18.** *Lamprocyclas margatensis* (Campbell and Clark). Scale equals 100 μm. All specimens were collected from sample Boso-8 (calcareous concretion between ash layers Am1 and Am2, Meigawa River).

Fig. 11. Lower Miocene siltstone intercalating tuff beds, Hota Group. Scale = 14 cm.

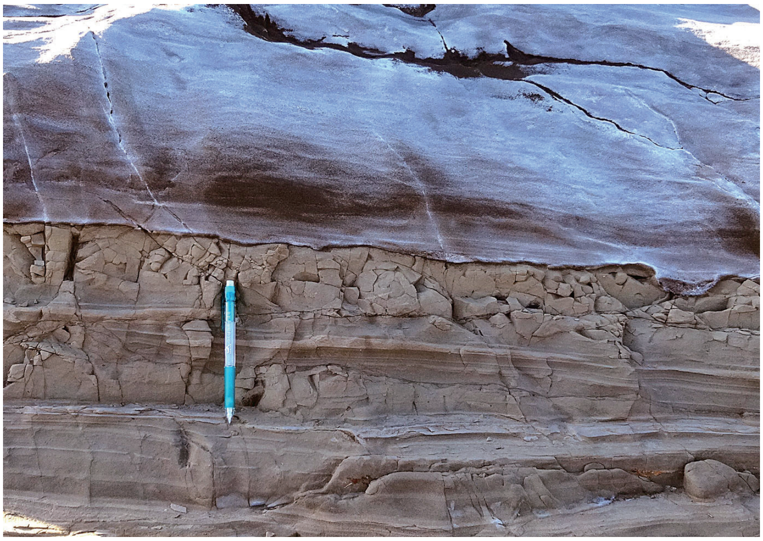

Fig. 12. The contact between the Shirahama Formation and the overlying Shiramazu Formation, which are characterized by brown-colored volcaniclastic sandstone and light gray-colored tuffaceous siltstone, respectively. Scale = 14 cm.

Stichocorys peregrina from the inland sections of the Shiramazu Formation.

At Shiramazu point, roadside rocky shore, it is possible to observe the upper part of the Shirahama Formation and the overlying basal part of the Shiramazu Formation and the conformable contact between them (Fig. 12). The contact can be easily identified because of their colors with good contrast.

Fig. 13. The Nojimazaki Conglomerate Member comprising gravity flow deposits at Cape Nojima-zaki.

STOP 2

Stop 2-1: Nojima-zaki—Pliocene trench-fill deposit (Chikura Group)

Cape Nojima-zaki is the southern tip of the Boso Peninsula. It is possible to observe a member of the Shirahama Formation, Nojimazaki Conglomerate Member, which distributes in the restricted area on the west side of the cape (Fig. 13). This conglomerate is composed of pebble- to cobble-sized gravels representing a channel fill deposit that could have been formed in the paleo-deep-sea trench. Most of the gravels are poorly sorted volcaniclastics. Minor components include plutonic rocks, sandstone, siltstone, chert and green tuff. Mud clasts are frequently observed. Early Cretaceous radiolarians have been found in the chert gravels. Both the lithofacies and shallow water fossils from the conglomerate indicate that they are gravity-transported shelf sediments, which flowed down the continental slope to the deep-sea trough.

Stop 2-2: Green Road—Pleistocene slope deposit (Chikura Group)

A 300 m thick sequence, Hata Formation, is dominated by interbedded tuffaceous sandstone and siltstone with frequent intercalation of pumice and scoria layers. A remarkable feature of this formation is the occurrence of large slumped sedimentary bodies. Calcareous nannofossils and magnetic polarity records indicate a late Pliocene to early Pleistocene (1.95–0.85 Ma) age for this formation (Kotake, 1988; Kotake et al., 1995). They also reported the occurrence of an early Pleistocene radiolarian species, *Eucyrtidium matuyamai*.

The roadside outcrop at this locality shows a remarkable example of chaotic sediments that consist of fragmented strata of various sizes within a sandy matrix (Fig. 14). This was

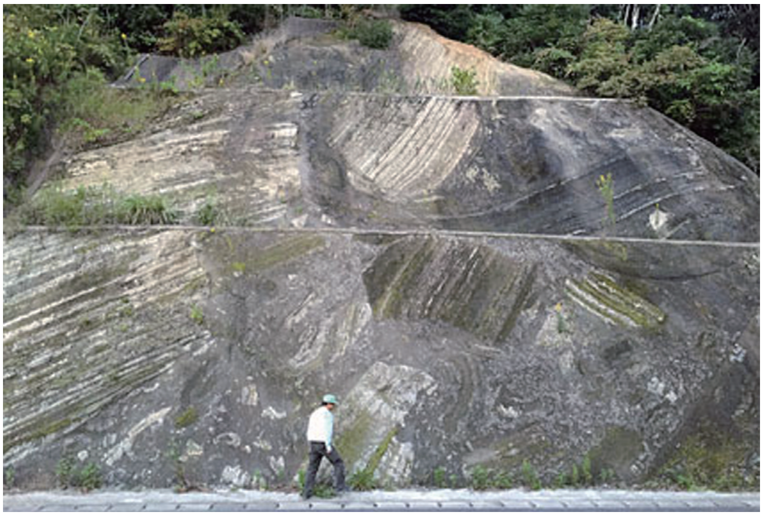

Fig. 14. Chaotic deformation features within the trench-slope cover sediments of the Hata Formation, Chikura Group.

introduced by Yamamoto et al. (2007) who suggested that a large earthquake could have triggered the sliding of slope deposits that moved down the paleo-slope surface as a liquefied sediment flow.

Stop 2-3: Kenbutsu—Coastal terrace uplifted during the 1923 Kanto Earthquake (Magnitude 7.9)

The Kanto Earthquake was one of the most catastrophic events generated by megathrust activities in modern Japan. This event devastated metropolitan Tokyo and its nearby areas and killed more than 100,000 people. Such major earthquakes in the Kanto region result in sudden coseismic uplift in the southern Boso Peninsula. Accumulations of these geomorphic changes affect the long-term evolution of coastal topography marked by coastal terraces. Fifteen or more steps have been detected that were formed during the Holocene and reflect the earthquake cycle. The highest terrace of the Holocene reaches 30 m above today's sea level.

An excellent place to see such uplifted coastal terraces is the Kenbutsu coast (Shishikura et al., 2016) (Fig. 15). The first step, called 'Taisho bench', above today's wave cut bench represents the coseismic uplift of the 1923 Kanto Earthquake. This vertical movement was 1.5 m. The second step of 3 m is larger than the first reflecting the larger magnitude of the related earthquake. This event is correlated to the Genroku Earthquake (M 7.9–8.5) that happened in 1703 and the terrace platform is called Genroku Terrace. The rock body of the terraces at this locality is the Kagamigaura Formation, the Minamiboso Group (Yamamoto and Kawakami, 2005; Kawakami and Shishikura, 2006).

Fig. 15. Uplifted coastal terraces on the Kenbutsu coast. Here a couple of steps reflecting two major earthquakes that occurred in 1923 and 1703 are clearly visible.

Fig. 16. Tilted tuffaceous sandstone bed set of the Chikura Group dominates the background of the Gake-Kannon temple.

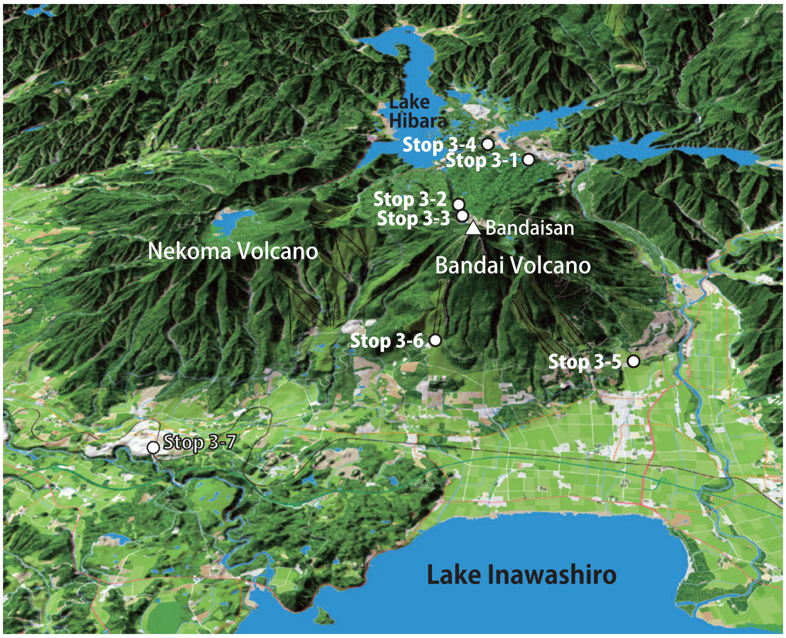

Fig. 17. Locality of the stops in Bandai Volcano. The base graphic map is provided from the Bandaisan Geopark Council.

Stop 2-4: Gake-Kannon—Pleistocene slope basin deposit (Chikura Group)

We will meet the Chikura Group again at this point. The vertical cliff exposes stratified tuffaceous sandstone strata (Fig. 16). A red colored temple dedicated to Kannon (Guanyin in Chinese), known as 'Gake-Kannon' (formally Daifukuji Temple), is placed at a high point on the cliff. 'Gake' means 'cliff' and 'Kannon' is a Goddess of Mercy in Buddhism.

STOP 3 (Fig. 17)

Stop 3-1: Bishamon-numa —Lake born by the 1888 eruption of Bandai Volcano

Bishamon-numa is the largest lake (150,000 m^2) in the Goshiki-numa area. This area contains over 30 various sized lakes and swamps which were born when water collected in the hollows among flow mounds (small conical hills) formed by the debris avalanche of the 1888 eruption. The water of each swamp is a mixture of the acidic ground water from the Aka-numa swamp located near the 1888 explosion caldera and other neutral ground water. Therefore Goshiki-numa swamps have various water qualities and show many beautiful colors.

Stop 3-2: Urabandai Ski Slope —The flow way of the 1888 debris avalanche

The 1888 phreatic eruption of Bandai Volcano caused Kobandai's collapse and debris avalanche. The way the debris avalanche ran is the present ski slope. Lake Hibara viewed to the north of this site was born after the damming of a river by the debris avalanche. On

Fig. 18. Explosion caldera and Aka-numa swamp formed by the collapse of Mt. Kobandai in 1888.

Lake Hibara there are several islands. They are flow mounds, called Nagare-yama in Japanese, formed by the debris avalanche, many of which are now under the water surface.

Stop 3-3: Aka-numa and Explosion Caldera ―Site of the Kobandai collapse in 1888

A big horseshoe-shaped caldera with a sheer cliff of bare rock was created by the collapse of Kobandai in the 1888 phreatic explosion (Fig. 18). Many strata of lava, volcanic breccia and volcanic ash seen on the surface of the cliff show the history of the past eruptions of Bandai Volcano. Aka-numa swamp was formed right after the collapse of Kobandai. The water of the swamp is strongly acidic and looks reddish brown, because mud containing iron hydroxide accumulates at the bottom of the swamp.

Stop 3-4: Museum of the Mt. Bandai Eruption

This museum is located on the northern slope of Bandai Volcano, called Urabandai. The museum mainly collects materials of the 1888 eruption of Bandai Volcano and natural environment around Mt. Bandai. The exhibition themes of the museum are as follows: the 1888 eruption of Mt. Bandai, villages swallowed up by rising lake waters, materials from the Mt. Bandai eruption, animals and plants around Mt. Bandai, volcanoes around the world, and the first seismograph in the world.

Stop 3-5: Mine-no-Oishi ―A large rock carried by the debris avalanche in 1888

When Bandai Volcano erupted in 1888, large andesitic rocks were carried by a debris avalanche from the place near the summit of Bandai Volcano to Mine Village through the Biwasawa River. Mine-no-Oishi is one of these rocks (Fig. 19). This giant rock has a height of 3.1 m and a length of 8.2 m. Because its present location is evidence that it was carried a

Fig. 19. Mine-no-Oishi, a large andesitic rock carried to Mine village by the debris avalanche in the 1888 eruption of Bandai Volcano.

much longer distance during the eruption than expected, this rock was designated as a National Monument of Natural History in 1941.

Stop 3-6: Resort Ski Slope —View point of the flow mound topography formed by the Okinajima debris avalanche

A lot of Nagare-yama (flow mounds) can be seen at the southwestern foot of Bandai Volcano. They are formed by a debris avalanche which was caused by a large-scale mountain collapse during a Plinian-style eruption about 50,000 years ago. Some flow mounds are around 500 m in diameter. The debris avalanche, called the Okinajima debris avalanche, also resulted in the damming of a river that flowed from the Inawashiro basin into the Aizu basin and gave birth to a large lake, the present Lake Inawashiro.

Stop 3-7: South of JR Bandai-machi Station —Internal structure of a flow mound formed by the Okinajima debris avalanche

This outcrop is one of the Nagare-yama formed by the Okinajima debris avalanche. At this site the rock facies and structure inside of the flow mound can be seen. A mass of large rocks of andesitic lava, which was once part of the old mountain of Bandai Volcano is surrounded by a muddy matrix (Fig. 20). Cracks like a jigsaw puzzle, called a jigsaw crack, can be seen on the rock surface. These are characteristic features of a debris avalanche.

Fig. 20. The internal structure of a flow mound formed by the Okinajima debris avalanche, which occurred about 50,000 years ago. A mass of large andesite rocks is surrounded by a muddy matrix.

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